Cost Effective 6.5% Silicon Steel Laminate for Electric Machines

Jun Cui[1], George Hadjipanayis[2], Jagadeesh Tangudu[3]

[1] Iowa State University

[2] University of Delaware

[3] United Technology Research Center

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Project ID: elt091

Overview

Timeline

- Start: October 1, 2016
- Finish: June 30, 2020
- Percent complete: 90%

Budget

- Total project funding
  - $3,835K (Federal)
  - $433K (Cost share)
- Funding for FY 2017: $1,489K
- Funding for FY 2018: $1,428K
- Funding for FY 2019: $1,351K

Barriers and targets

- Magnet cost and rare-earth element price volatility
- Non-rare-earth electric motor performance
- 2020 DOE EDT cost target of $4.7/kW and power density target of 5.7 kW/L.

Partners

- Iowa State University (Lead)
- Ames Laboratory
- United Technology Research Center
- University of Delaware

Relevance

- MnBi based non-rare earth magnet:
  - Objective: Scale up and enable MnBi magnet for motor application
  - Impact: The price of MnBi bulk magnet (8 MGOe) is estimated at $11/kg ($1.5/J), while NdFeB Grade N52 (52 MGOe), was $144/kg in Jan. 2020 ($2.6/J).

- Electrical steel with 6.5%Si:
  - Objective: Solve the brittleness problem and enable 6.5%Si steel for motor application
  - Impact: Reduces iron loss at higher frequency, improve motor power density and efficiency

- Non-rare earth motor
  - Objective: Demonstrate motor with MnBi as permanent magnet and 6.5%Si steel as the soft magnetics
  - Impact: Improve non-rare earth motor power density

Milestones

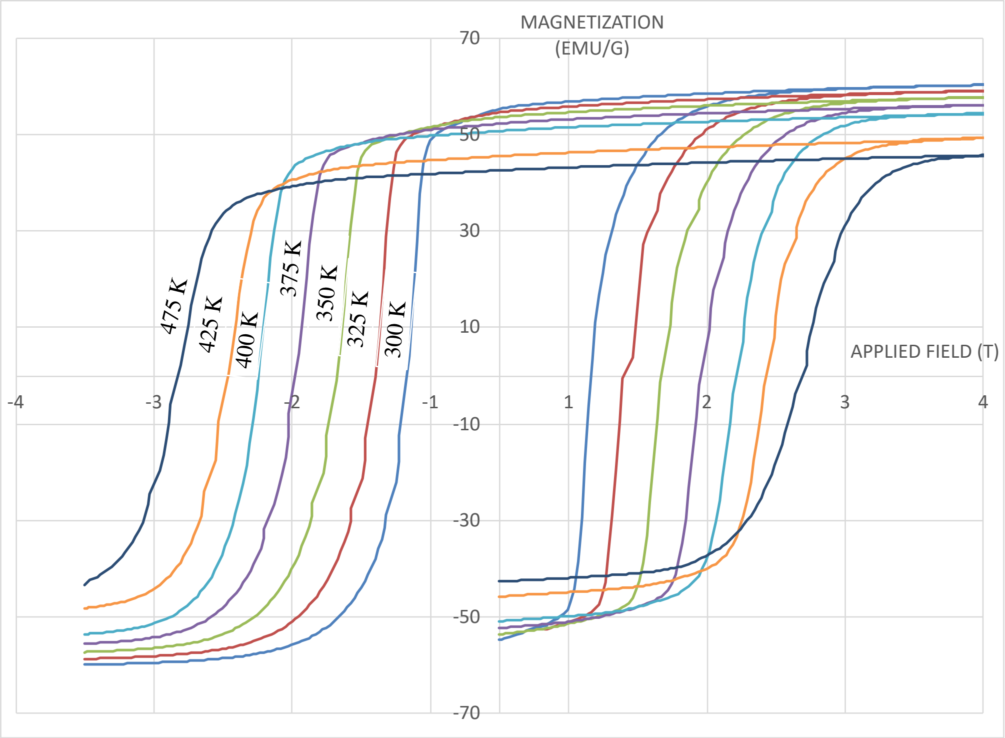
Tasks #	Description	2017				2018				2019				2020		
1	MnBi magnet (UDEL and ISU)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
1.1	Fabricate 8.5 MGOe (ISU)															
1.1.1	Small scale 8.5 MGOe magnet demonstration (5 gram)	✓	✓													
1.1.2	Design/construction of large warm-compaction setup		✓	✓	X											
1.1.3	Large 8.5 MGOe MnBi magnet fabrication					✓	✓	✓	✓	✓	✓	✓	✓			
1.2	Develop 10 MGOe MnBi magnet (UDEL)															
1.2.1	Setup high speed melt-spinning system	✓	✓													
1.2.2	Produce 90% amorphous MnBi flakes (UDEL)			✓	✓											
1.2.3	Develop field annealing method (UDEL)					✓	✓	✓	✓							
1.2.4	Scale up 10 MGOe magnet process (ISU)									✓	✓					
2	Fe-6.5%Si stator (ISU)	1	2	3	4	1	2	3	4	1	2	3	4			
2.1	Investigation ductility of melt-spin Fe-6.5%Si	✓	✓	✓	✓											
2.2	Melt-spun flake production															
2.3	Flake compact and sintering					✓	✓	✓	✓							
2.4	Stator thickness optimization							✓	✓	✓	✓					
2.5	Scale-up cross section											✓	X			
3	Task 3: 400 Hz PM motor (UTRC)	1	2	3	4	1	2	3	4	1	2	3	4			
3.1	Motor design	✓	✓	✓	✓											
3.2	Construction with dummy magnetics					✓	✓	✓	✓	✓	✓	✓	✓			
3.3	Motor evaluation												✓	✓	✓	✓
3.4	Retrofit with MnBi and ISU stator and evaluation											X	X			

MnBi Magnet

Challenges (MnBi)

Advantages of MnBi

- Large coercivity that is increasing with temperature.
- Theoretical energy product $(BH)_{max}$ 20 MGOe



Experimental M-H-T data showing increasing coercivity with increasing temperature

Challenges of MnBi

- Mn precipitation is inevitable, difficult to maintain high purity and high magnetization, which is limited at ~90 kG, any impurity will reduce the energy product
- At 340°C LTP-MnBi decomposes to HTP-$Mn_{1.08}Bi$ and liquid Bi, making it difficult to fabricate bulk magnet using the conventional sintering or warm compaction method
- Need to magnetically separate each grain in order to maintain magnetic coercivity

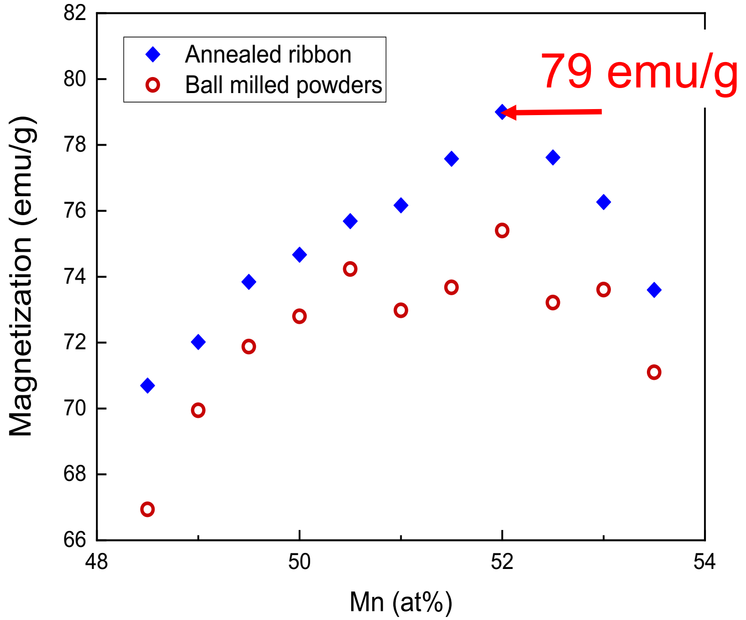
Approach (MnBi)

- Refine existing powder synthesis and magnet fabrication process:
  - Control oxygen
  - Control particle size
- Consistently produce bulk magnet with 8 MGOe
- Use amorphous feedstock to reduce Mn precipitation and improve energy product from 8.5 to 10 MGOe

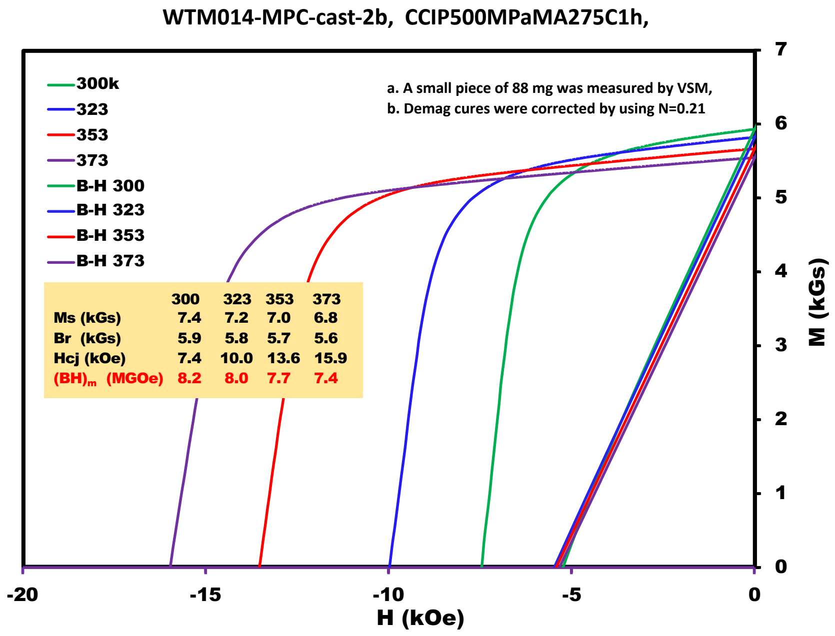
	End results and annual go/no-goes
Yr 1	1. Produced 8 MGOe MnBi magnet (5 gram) 2. Produced 5 gram MnBi with 90% amorphous
Yr 2	1. Fabricated one 100 gram/pcs 8 MGOe MnBi magnet 2. Fabricate one small 10 MGOe MnBi (>2 gram)
Yr 3	1. Deliver 300 pieces of 8 MGOe MnBi magnet (10 gram each) machined to the desired dimension and coated

Technical Accomplishments (MnBi)

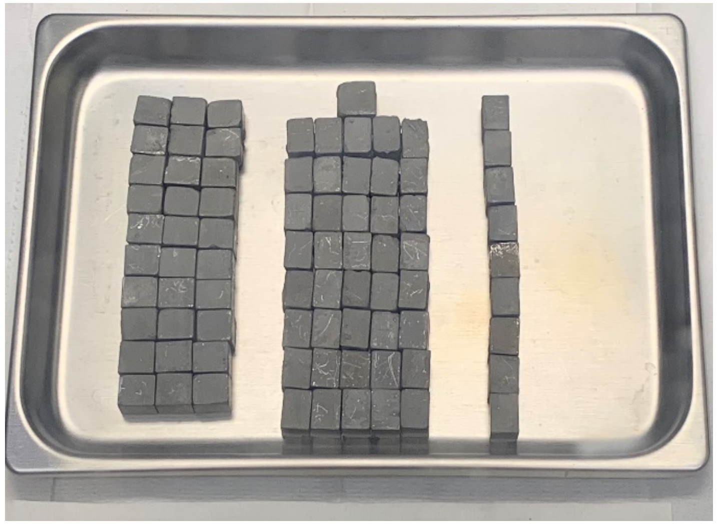
- Achieved a new record of saturation magnetization of 79 emu/g (theoretical limit is 82 emu/g)
- Milestone of bulk 8.5 MGOe is closely met (8.2 MGOe demonstrated), 80 magnets were fabricated (deliverable was 300)
- Demonstrated 12 MGOe using a small $Mn_{40}Bi_{45}Mg_{3}In_{0.5}Sb_{0.5}$ magnet (0.5 gram)



Measured magnetization of alloys with different amount of manganese



M-H curves of the MnBi bulk magnet at 300, 323, 353, and 373 K



Picture of 80 pieces of bulk magnets
Each weight about 9 gram, 1cm^3

6.5% Si Steel

Advantage and Challenge (6.5% Si Steel)

Table of physical properties of various soft magnetic materials

Type	Materials	Bs (T)	Hc (A/m)	$10^3\mu_r$ 1 kHz	R ($\mu\Omega$.cm)	λ (ppm)	$W_{1.5/50}$ (W/kg)	$W_{10/400}$ (W/kg)	Ref
Crystalline	Electrical Steel, 0.2mm, NGO, 3.2% Si	2	26	15	57	8	0.7-1.2	11	[1,5]
	Electrical Steel, 0.2mm, NGO, 6.5% Si	1.7	45	19	82	0.01	0.6	8.1	[1, 2]
	Molypermalloy, 0.5mm, Ni78Fe17Mo5	0.65-0.82	0.25-0.64	100-800	60	2-3	0.07	0.3	[3,4]
	Hiperco 50, Fe49Co49V2	2.4	16-400	5-50	27	60	4	10	[4]
Nano-crystalline	FINEMET, $Fe_{73.5}Si_{13.5}Nb_3B_6Cu_1$	1.2	0.5-1.4	80	110	0-2	--	1.1	[4-6]
	NANOPERM, $Fe_{88}B_4Zr_7Cu_1$	1.5-1.6	2.4-4.5	48	56	~0	--	3	[4-6]
	HITPERM, $(FeCo)_{44}Zr_7B_4Cu_1$	1.6-2.0	80-200	1-10	120	36	--	20	[4-6]
Amorphous	Metglas, Fe78Si9B13	1.54	3	2.1	135	27	0.7	2-5	[7]
	Metglas 2650CO, $Fe_{67}Co_{18}B_{14}Si_1$	1.8	3.5	50	123	35	0.3	3	[4,8]
Ferrite	Ferrite, MnZnFeO	0.36-0.5	10-100	0.5-10	10^7-10^8	5	--	--	[4]
	Ferrite, NiZnFeO	0.25-0.42	14-1600	0.01-1	10^{11}	-20	--	--	[4]

Advantage:

Low cost;
High magnetization;
High e-resistivity;
Low magnetostriction;
Suitable for high power density machine

Challenges:

Too brittle to be manufactured using the cost effective cast/hot-roll/cold-roll process

REF
[1] http://www.jfe-steel.co.jp/en/products/electrical/supercore/jnex/04.html
[2] H. Haiji, K. Okada, T. Hiratani, M. Abe, M. Ninomiya, J. MMM, 160 (1996) 109-114
[3] G. Herzer, Ch. 3. Nanocrystalline soft magnetic alloys, Handbook of Magnetic Materials, V.10, 1997
[4] O. Gutfleisch, M. Willard, E. Bruck, C. Chen, S.G. Sankar, J.P. Liu, Advanced Mats. (2011), 23, 821-842
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[6] M. McHenry, M. Willard, D. Laughlin, Prog. Mats Sci, 44 (1999(, 291-433
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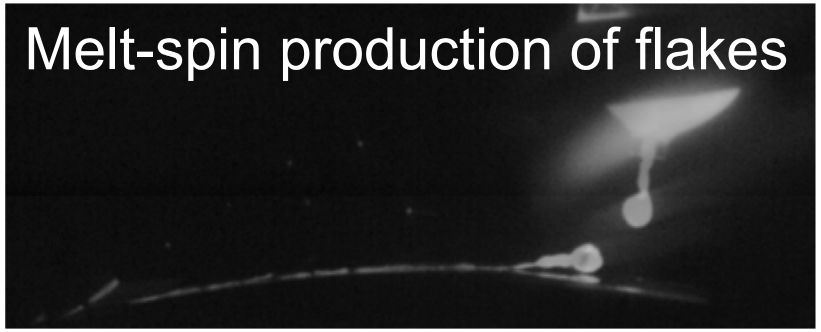
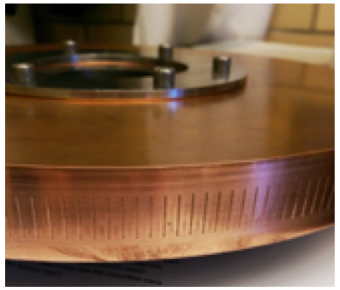
Approach (6.5%Si Steel)

- Use rapid solidification to suppress the deleterious ordering phase and produce ductile thin flakes.
- Dip-coat flakes with thin CaF_2 layer for insulation.
- Consolidate ductile flakes into near-net-shape part with laminated internal structure.

	End results and annual go/no-goes
Yr 1	1. Delivered 10 gram of ductile Fe-6.5%Si flakes (30 mm thick, 1x1 mm^2, 180º bending no crack)
Yr 2	1. Delivered Fe-6.5%Si rings with 0.1, 0.4, 1, and 4 mm thickness (OD: 1.5”, ID: 1.25”, 98% dense, various levels of oxidization) 2. Validated power loss $W_{10/400}$<6 W/kg for the ring with 0.4 mm thickness.
Yr 3	1. Deliver 8” OD stator laminate with W10/400<6 W/kg 2. Project manufacturing cost for small scale mass production

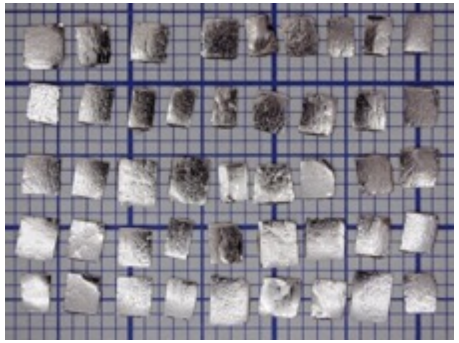
Technical Accomplishments (6.5%Si Steel)



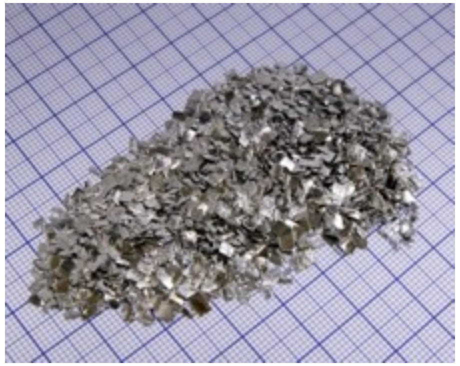


Grooved wheel breaking continuous ribbon to flakes

- Developed the process for producing flakes (2x2x0.1 mm^3)
- Approximately 75% yield of the flakes with the desired size
- System capable of 500 gram per batch was installed



<u>2017 (1st year)</u>
Flakes with desired size produced in 5 gram quantity

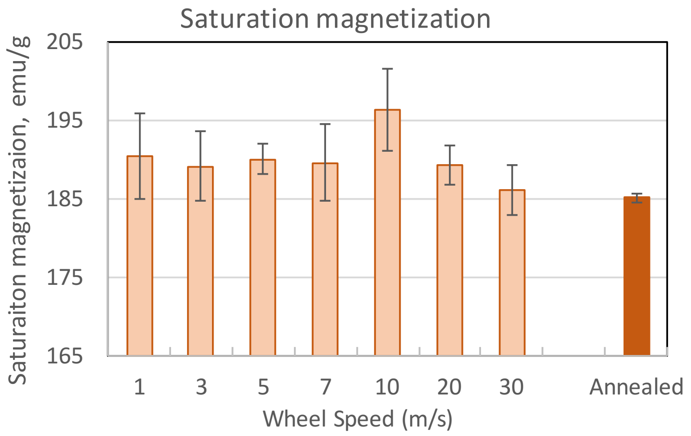


<u>2018 (2rd year)</u>
Flakes with desired size produced in 150 gram quantity

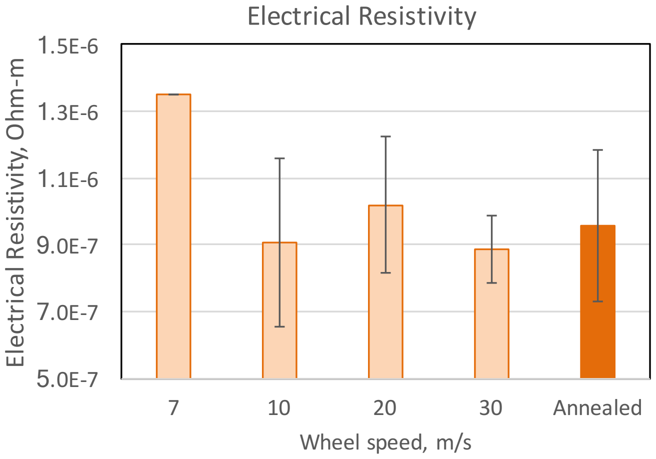
<u>2019 (3rd year)</u>
Flakes coating process was developed

Technical Accomplishments (6.5%Si Steel)

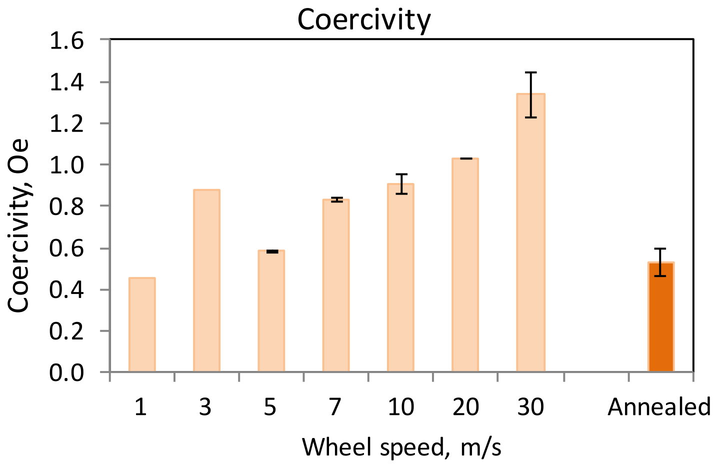
Relationship between wheel speed and physical properties established



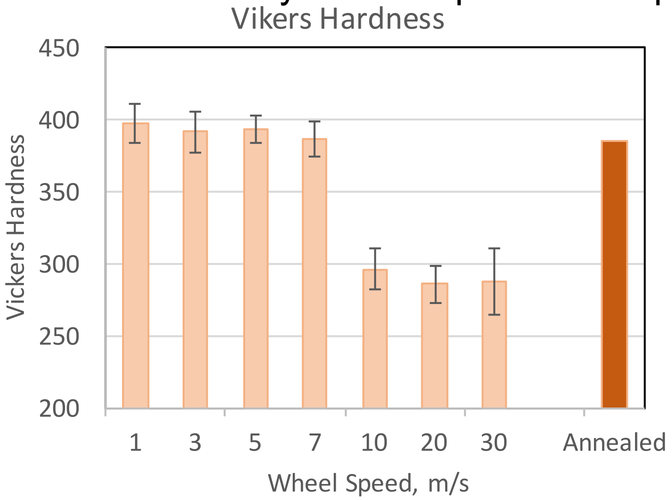
Saturation magnetization vs melt spun wheel speed



Electric Resistivity vs melt spun wheel speed



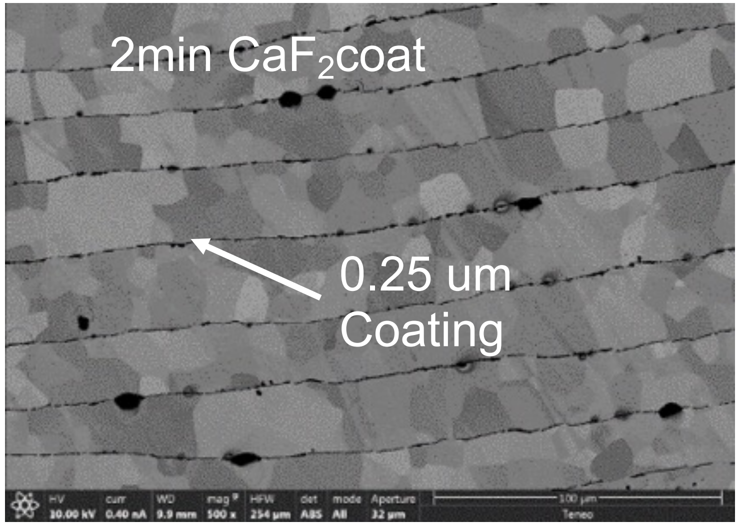
Coercivity vs melt spun wheel speed

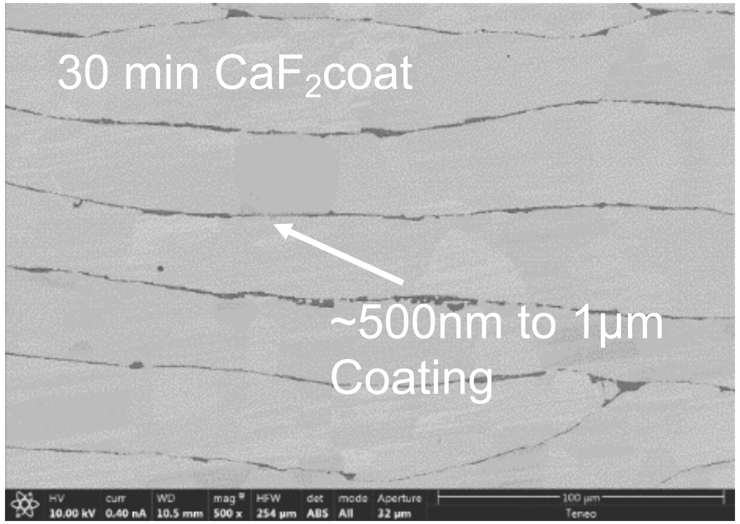


Hardness vs melt spun wheel speed

Technical Accomplishments (6.5%Si Steel)

- Coating thicknesses (0.25-20 μm) has been investigated.
- Mg_2SiO_4 effectively increased the resistivity up to 800 times.

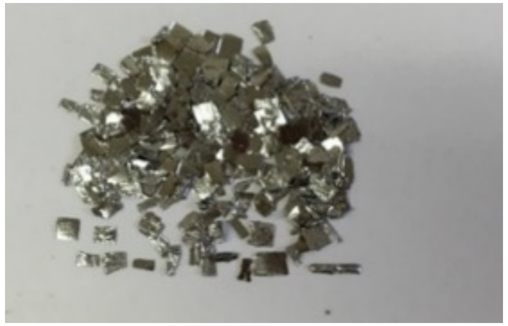




Coating	Density g/cc	Densification	Resistivity μΩ-cm
None	7.48	100%	81.36-84.29
CaF_2, 2min	7.35	98.3%	108.2-93.5
CaF_2, 30min	7.32	97.8%	139.1-115.4
CaF_2, 2h	6.85	91.6%	322.5-294.5
CaF_2, quad coat	5.99	80.1%	339.5-228.8
10% MgO, 30s dip	6.86	91.7%	510.1-259.2
50% MgO, 30s dip	4.70	62.8%	66k-22k
50% MgO anneal	6.34	84.8%	1111.5-688.9

Technical Accomplishments (6.5%Si Steel)

Coreloss performance met/exceeded the expectation
- 0.2mm sample achieved record low iron loss at 400 and 1000Hz.
- 0.1mm sample has W10/400 of 6.1W/kg



Melt-spun flakes

Hot press →

Consolidated flakes

→ 1100°C x 2h annealing + Slice →

A ring sliced from the consolidated flakes

		Ameslab GO2P23	3.2% Si steel	Ameslab GO2P23	JNHF	Ameslab GO2P23	JNEX
		Fe-6.5Si	Fe-3.2Si	Fe-6.5Si	Gradient Fe-6.5Si	Fe-6.5Si	Fe-6.5Si
thickness	(mm)	0.33	0.35	0.2	0.2	0.1	0.1
W10/400	(W/kg)	10.8	14.4	7.2	14.5	6.1	5.7
W10/1k	(W/kg)	45.7	62.0	27.3	29.1	20.2	18.7
DC,μMax		28.7k	18.0k	28.4k	3.9K	25.8k	23.0k

10 kW 400 Hz motor

Performance Metrics & Materials Considered

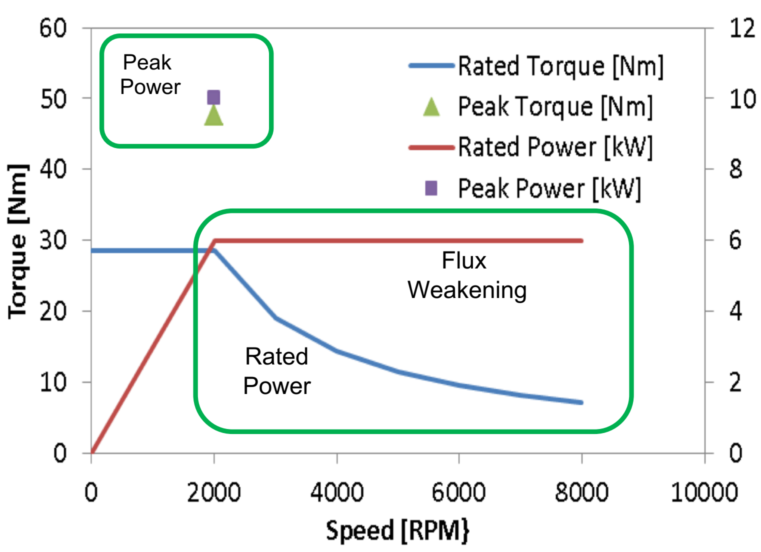
Machine Performance Specifications for 10 kW Peak, 6 kW Rated Power

Performance Metric Targets		
Cost	Specific Power	Power Density
≤$4.7/kW	≥1.3 kW/kg	≥5.7 kW/Liter

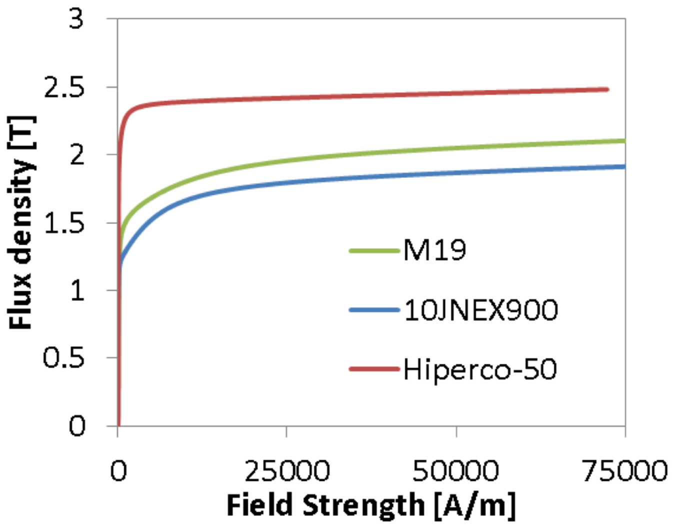
Target Motor Specifications

Specifications	Units	Values
Peak Power	kW	10
Continuous Power	kW	6
Max Speed	RPM	8000
Min Frequency	Hz	300
Voltage	V	325
Max per Phase Current	A rms	35
Characteristics Current	A rms	< 35
Weight	kg	7.69
Volume	l	2.2
Unit Material Cost	$	47
Max Efficiency @ 1/2 Speed & 1/2 Torque	%	95%
Based Speed	RPM	2000
Peak Torque @ Rated Speed	Nm	47.75
Rated Torque @ Rated Speed	Nm	28.65
Max Speed	RPM	8000
Torque @ Max Speed	Nm	7.16

Torque/Power vs. Speed



Soft Magnetic Properties

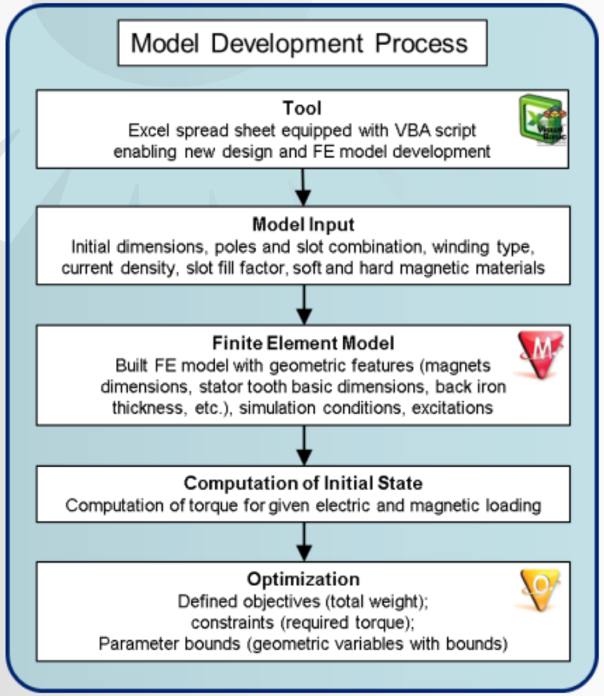


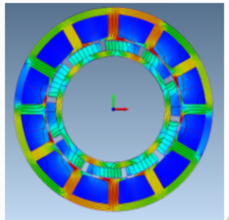
Hard Magnet Properties

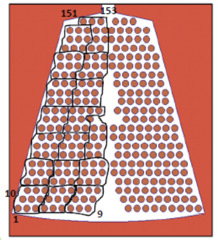
Material	Remnant Flux Density [T]	Coercive Force [kA/m]	Energy Product [MGOe]	Cost [$/kg]
NdFeB48	1.39	1060	46.2	80
MnBi	0.6	405.8	8.4	10
Ferrite	0.45	33.5	4.9	5

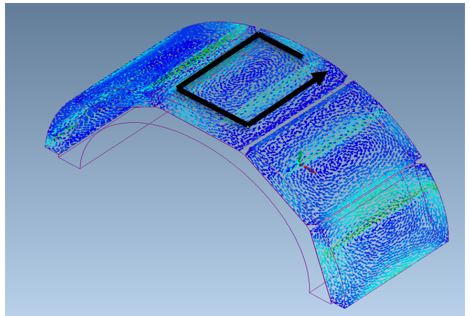
Modeling Approach: Multi-Physics

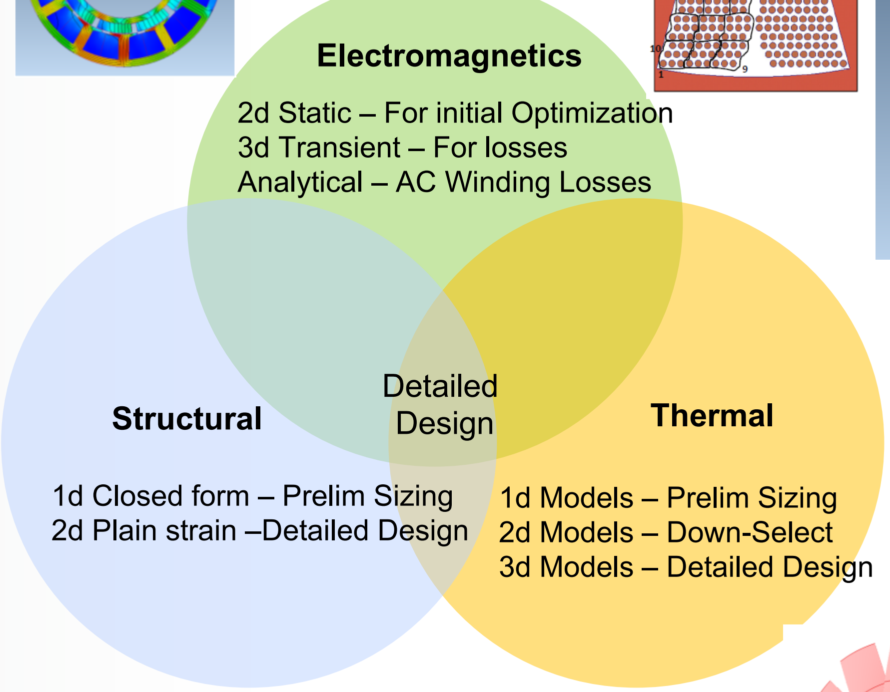
Multi-physics modeling to address some of the key risks identified

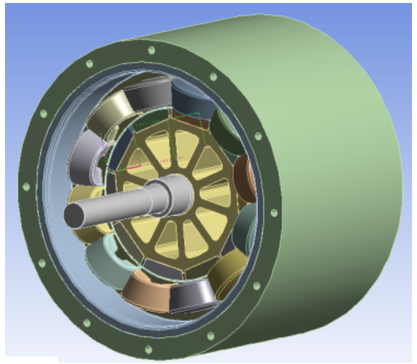


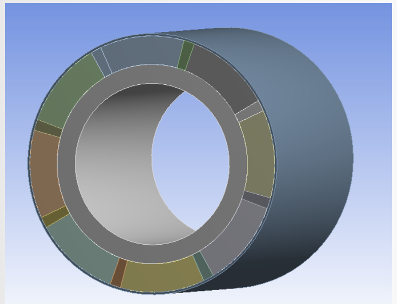


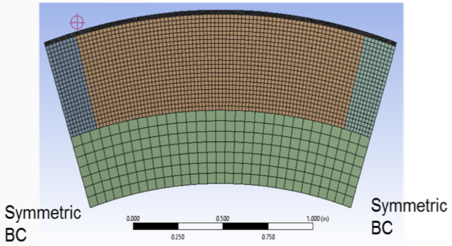


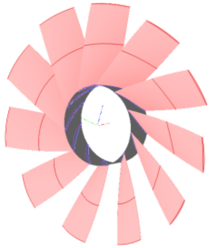


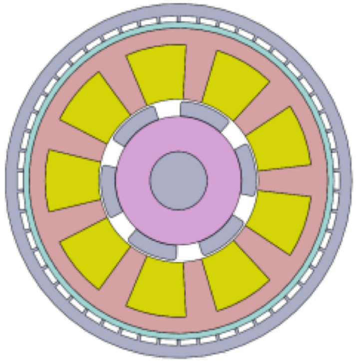






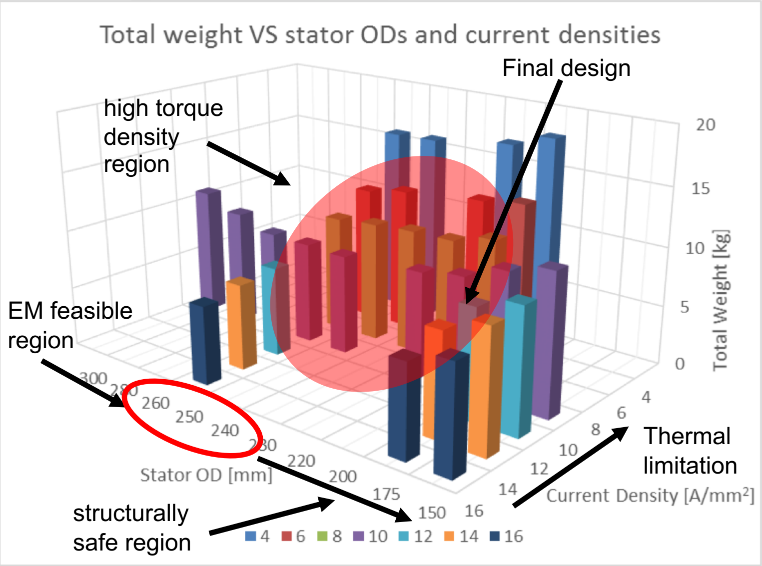






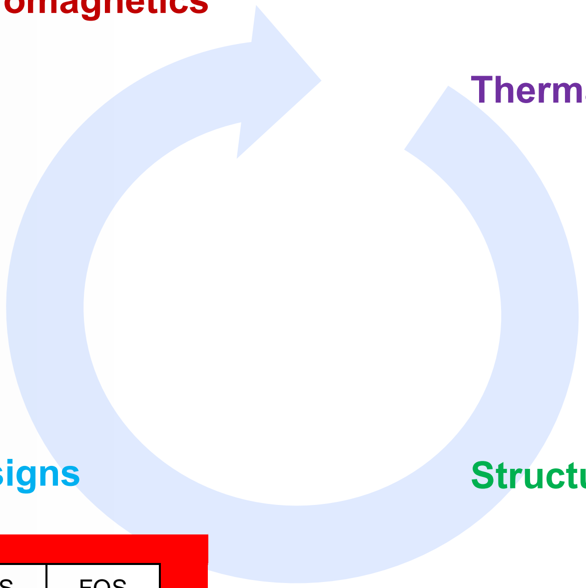
Design Iteration & Down Select

Design down select with multi-physics modeling and constraints



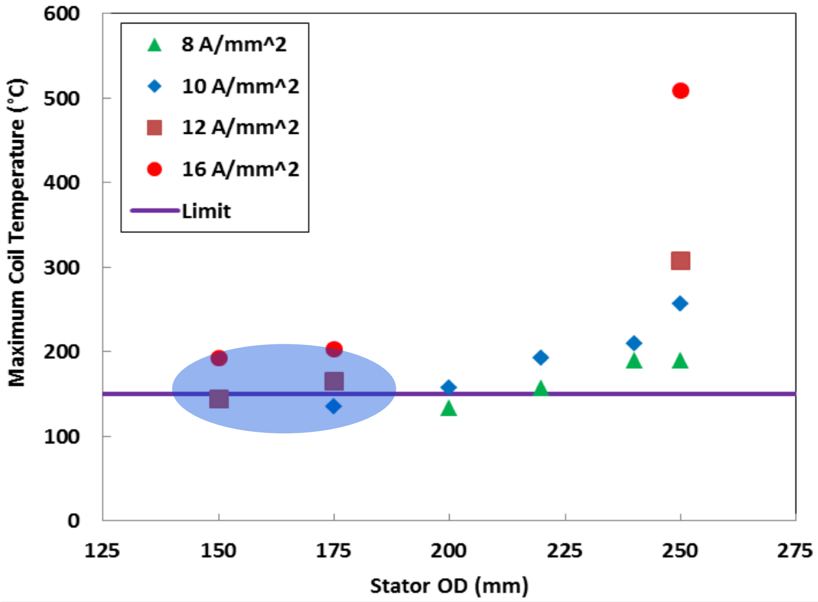
Electromagnetics

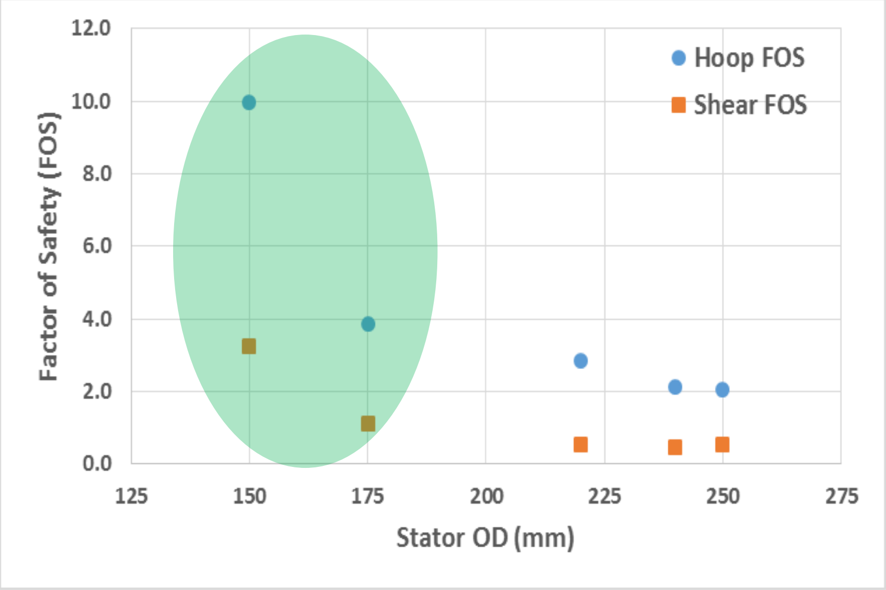
Thermal



Structural

Down Selected Designs





Stator OD	Rotor OD	Stack length	Total weight	Current density	Max Tempearture	FOS Hoop	FOS Shear
[mm]	[mm]	[mm]	[kg]	[A/mm^2]	[ºC]		
150	96	126.4	10.32	12	145	3.29	1.19
175	101.5	89.3	11.24	10	135	9.93	2.04
175	122.5	83.4	9.2	12	148	4.5	1.3
200	128	59.8	9.44	10	158	3.51	0.99

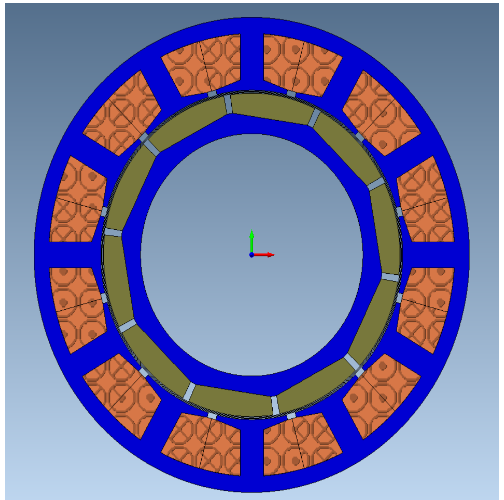
Prototype Design: Final Parameters

Final prototype design key parameters

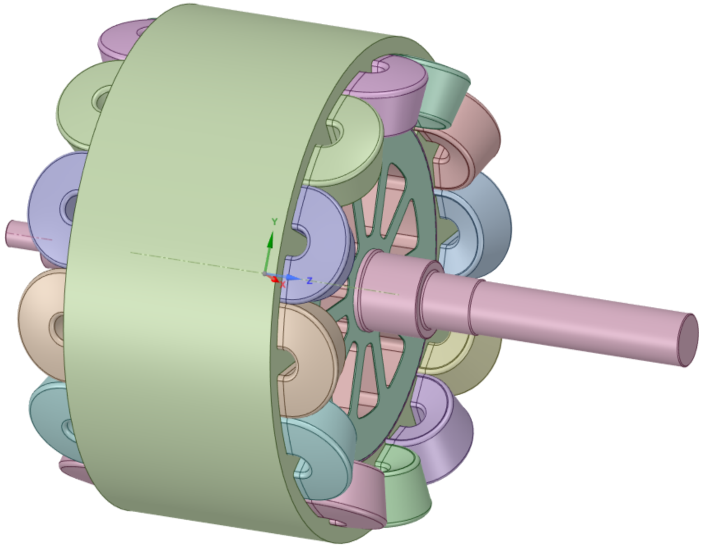
Key Dimensions

Number of slots	12
Number of poles	10
Number of phases	3
Slot per pole per phase	2/5
Stator outer diameter [mm]	180
Magnet thickness [mm]	7.0
Rotor OD [mm]	108.5
Air gap [mm]	1.135
Turns per coil	26
Turns per phase in series	104
Copper mass [kg]	3.4
Lamination mass [kg]	4.9
Magnet mass [kg]	1.8
Total mass [kg]	10.1
Power density [kW/kg]	0.99

2d Cross Section



3d Model with End Winding



Measured Design Parameters

Parameter	Units	Values
D-Axis Inductance	mH	2.2
Q-Axis Inductance	mH	2.2
Resistance:	Ohms	0.102
Back EMF Constant	Vrms/kRPM	43.92
Torque Constant	Nm/Arms	1.22

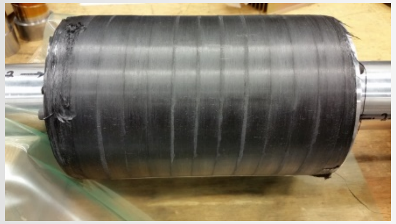
Prototype Building & Experimental Setup

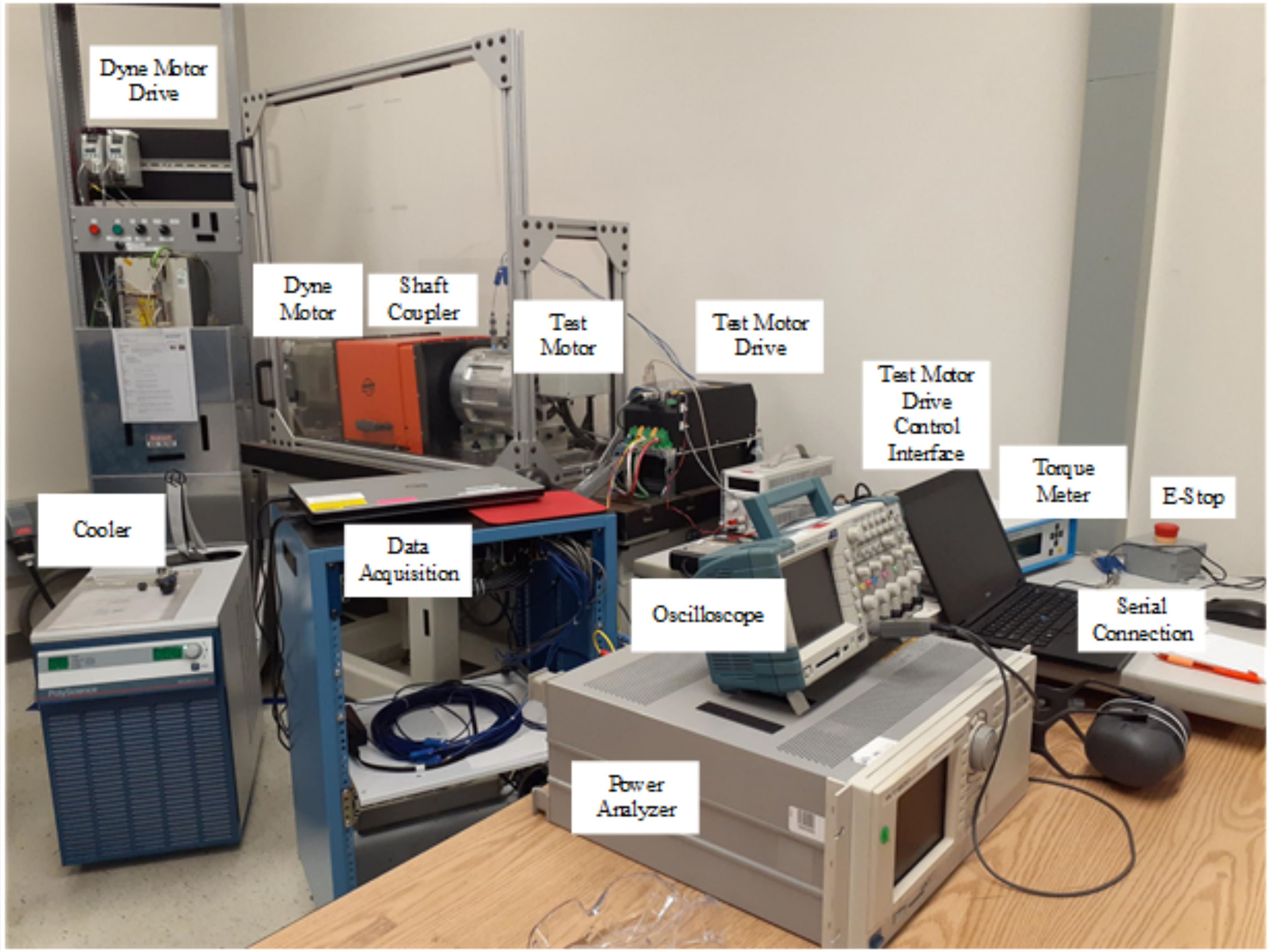
First Motor Prototype with Siemens Dyne and Phase Motion Drive

Stator & Rotor Laminates

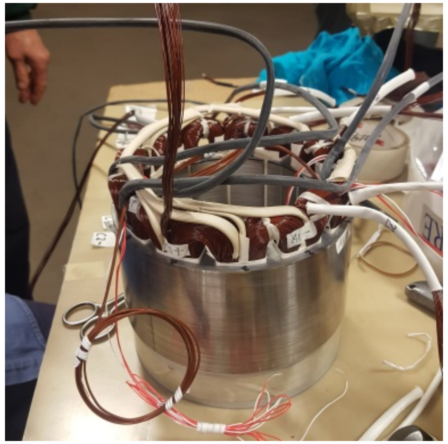
Rotor with Magnets

Rotor with Carbon Composite

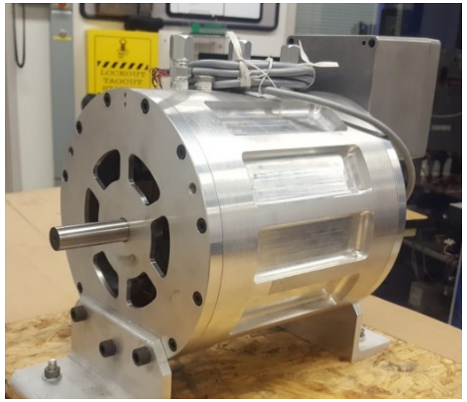




Stator Core with Coils



Motor with Cooling Jacket

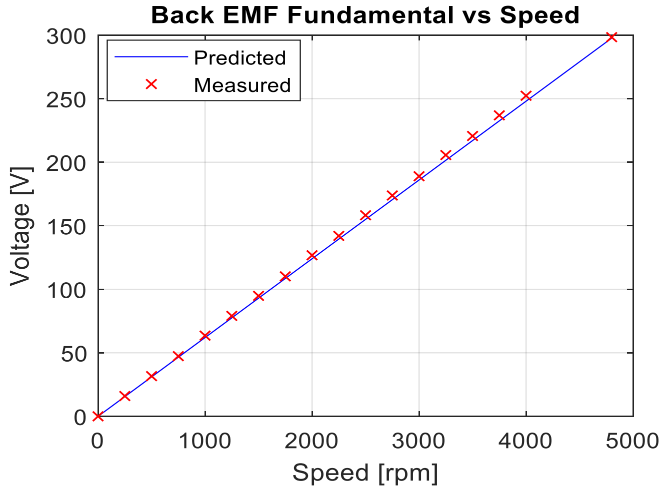


Basic Parameters: Back EMF

Open Circuit Back EMF voltage matches very well

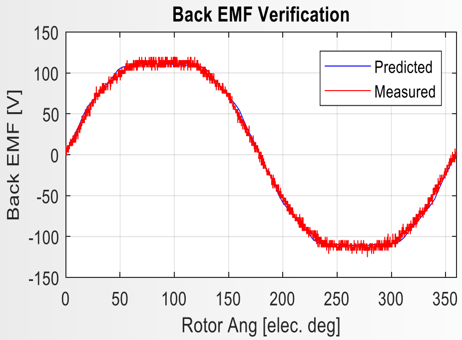
Resistance and Inductance

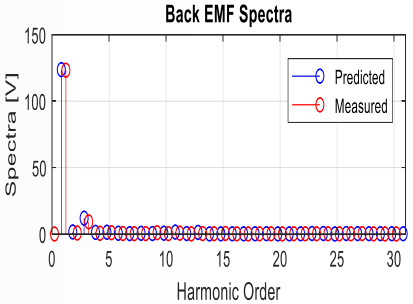
	Predicted	Measured	Difference	Diff. Per.
R_a [mW]	102	111.0	9	8.8%
R_b [mW]	102	111.5	9.5	8.9%
R_c [mW]	102	111.1	9.1	8.7%
L_a [mH]	2.2	2.25	0.05	2.2%
L_b [mH]	2.2	2.29	0.09	2.3%
L_c [mH]	2.2	2.27	0.07	2.3%



	Predicted	Measured
Fund. Back EMF constant [Vrms/krpm]	43.9	44.7

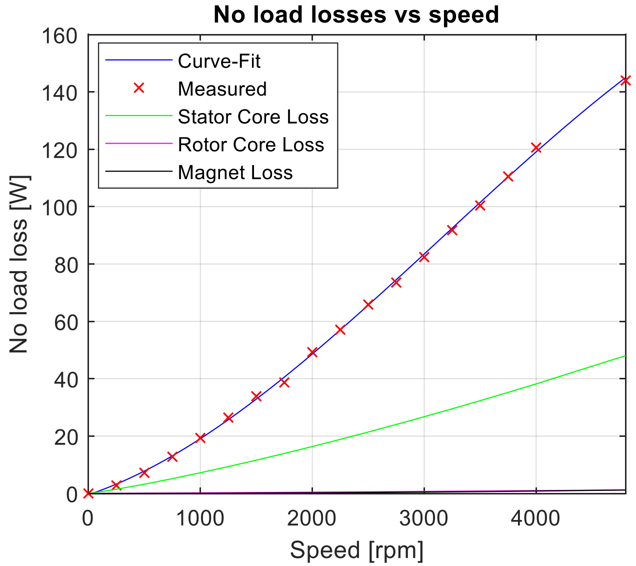
Phase Back EMF & Harmonics





Spectra Comparison

	Predicted [V]	Measured [V]	% Error
Fundamental	124	123	1.8
3rd harmonic	11.9	9.2	-
5th harmonic	1.4	0.97	-
7th harmonic	0.31	0.27	-
11th harmonic	1.47	0.64	-
13th harmonic	1.21	0.34	-

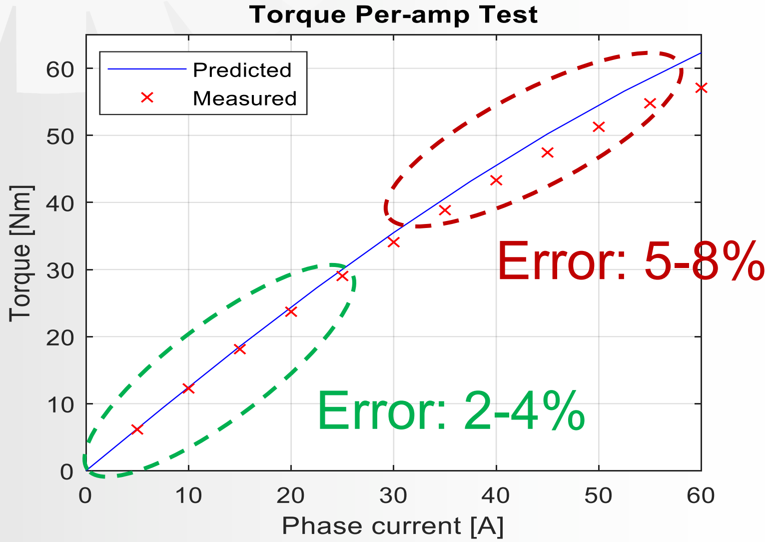


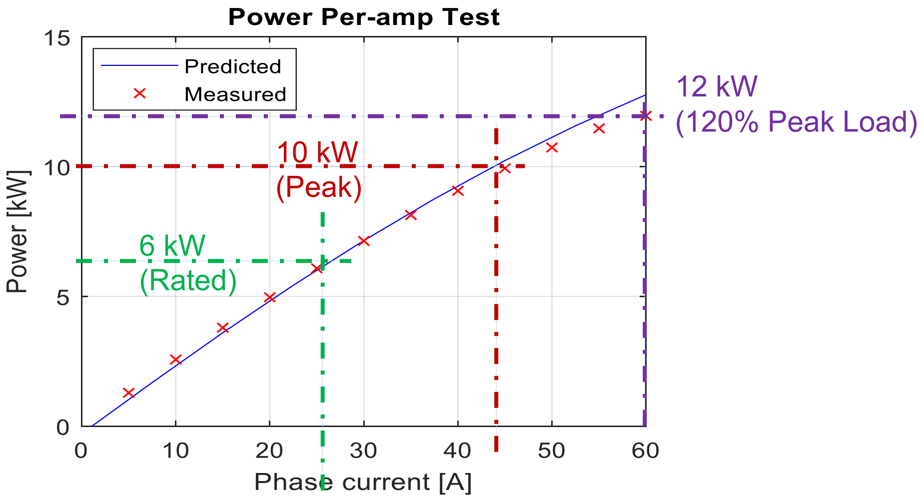
Torque vs Current: Torque Constant

Torque measurements match well at lower current but saturation impacts…

At base speed of 2000 rpm, current varied from zero to peak current.

- Tested the motor at rated (6 kW), peak (10 kW) and 120% peak load (upto 12 kW)
- Efficiency measurements with measured losses (Cu loss updated with measured phase resistance)





For Linear Region	Predicted	Measured
Torque constant [Nm/Arms]	1.22	1.21

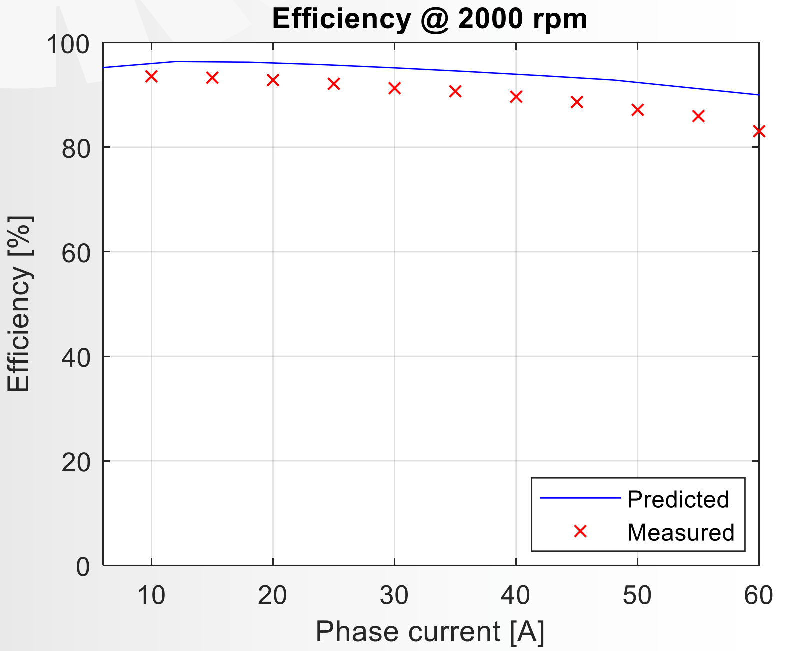
- Torque seems to match well at light load but starts to taper off at high currents
- Possible causes include saturation of the material different from the datasheets

Torque vs Current: Losses and Efficiency

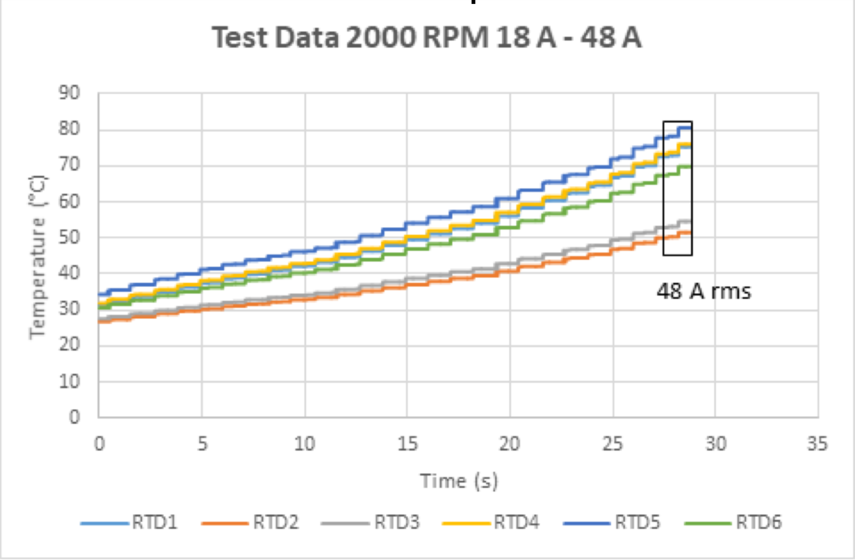
Efficiencies prediction are higher and transient temperature are with-in range

At base speed of 2000 rpm, current varied from zero to peak current.

- Efficiency measurements with measured losses (Cu loss updated with measured phase resistance)



Transient Temperatures

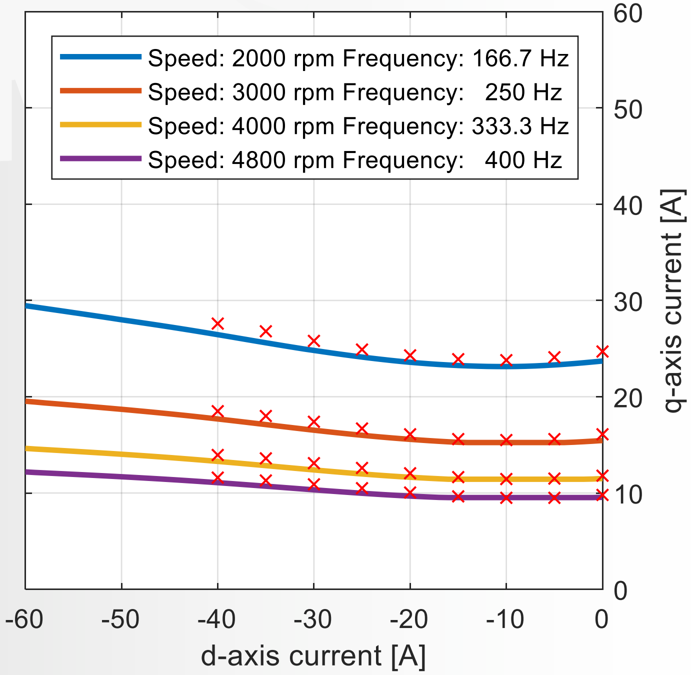


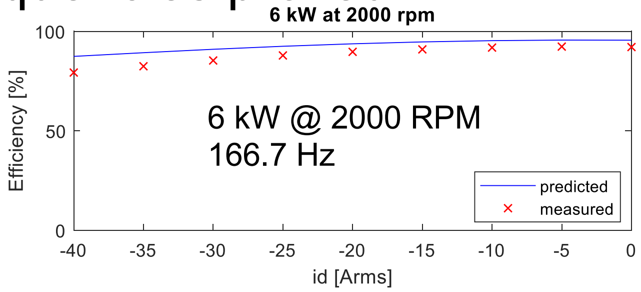
- As anticipated, predicted efficiencies are higher than measured efficiencies, due to missing loss components such as stray load losses, non-sinusoidal excitation, unbalanced mechanical loads
- Transient temperature rise is with-in max operating temperatures
- Variation in adjacent end winding RTD temperatures noticed, further investigation – in-progress

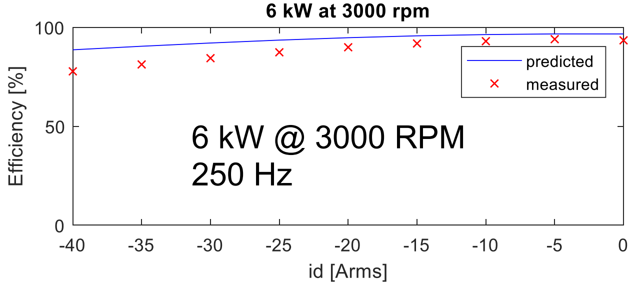
Field Weakening Performance

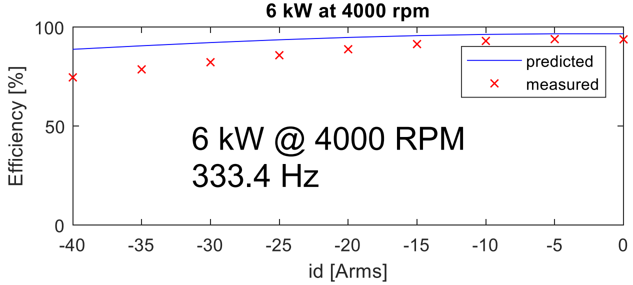
Flux weakening performance for 6 kW at various frequencies proved

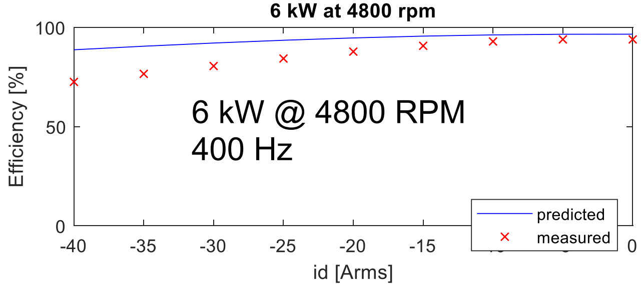
Current contour for various speed at 6kW











- Efficiency measurement at low Id match well
- Error in efficiency starts to increase with deeper flux weakening

Conclusions & Next Steps

Motor prototype built, validated and compare well with model prediction

Phase-III

- Experimental validation – Complete

- Tasks completed during phase-III
  - Completed motor prototype build
  - Integrated the test motor with dyne setup
  - Completed testing of the motor at 20% over load at peak power (target: 10 kW)
  - Completed flux weakening characterization upto 400 Hz (target frequency > 300 Hz)

Next Steps
  - Complete testing (no cost extension) – currently put on-hold due to facility closure (COVID-19)
  - Cost model for proposed motor materials/architectures

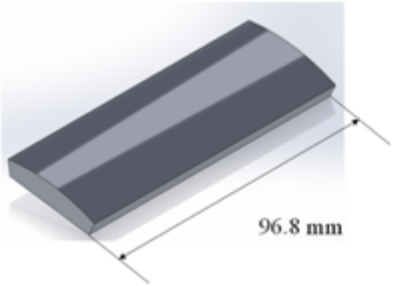
Responses to Previous Year Reviewers' Comments

Reviewer comments	Reply
The approach is good, but there are still significant challenges in terms of scalability especially for the 6.5%Si laminations. It was not clear that these materials can come close to meeting the new DOE targets.	We have reached a preliminary agreement to pass the knowledge to Metglas, the company capable of large scale production of 6.5% Si thin sheet.
The progress is overall good, but comprehensive evaluations, such as efficiency and power density, is needed for electric machines that use this new material.	The evaluation of the first prototype built with 6.5%Si steel appears to be satisfactory; however, prototypes with higher frequency should be built and tested
The project is relevant to efficiency targets but not so much to power density targets.	The project aims at meeting DOE 2020 power density while maintaining 90% efficiency. Such efficiency is critical for sustaining a reasonable driving range.

Collaboration and Coordination

Ames Laboratory	Melt-spin flakes production; Bulk magnet production
United Technology Research Center	Motor design and testing
University of Delaware	Amorphous MnBi flakes production
Electron Energy Corp.	Dummy magnet simulating the performance of MnBi magnet
JFE Steel Corp.	Commercial 6.5 Si% steel sheet (0.1 mm)
Metglas	Scale-up melt-spin 6.5%Si steel production
Leppert-Nutmeg Inc.	Motor construction

Remaining Challenges and Barriers



- MnBi:
  - Scale up
  - Increase energy product to 10 MGOe
- 6.5% Si steel:
  - Mass production
- Motor
  - Improve power density from 4 kW/L (2020 target) to 33 kW/L (2025 target)

Proposed Future Research

- MnBi
  - Further improve MnBiMgSn bulk magnet energy product to 15 MGOe, scale up and then mass produce
- 6.5% Si steel
  - Next generation Silicon steel with core-loss close to Sendust
- Non-Re motor
  - 1 kHz non-REPM motor

Any proposed future work is subject to change based on funding levels.

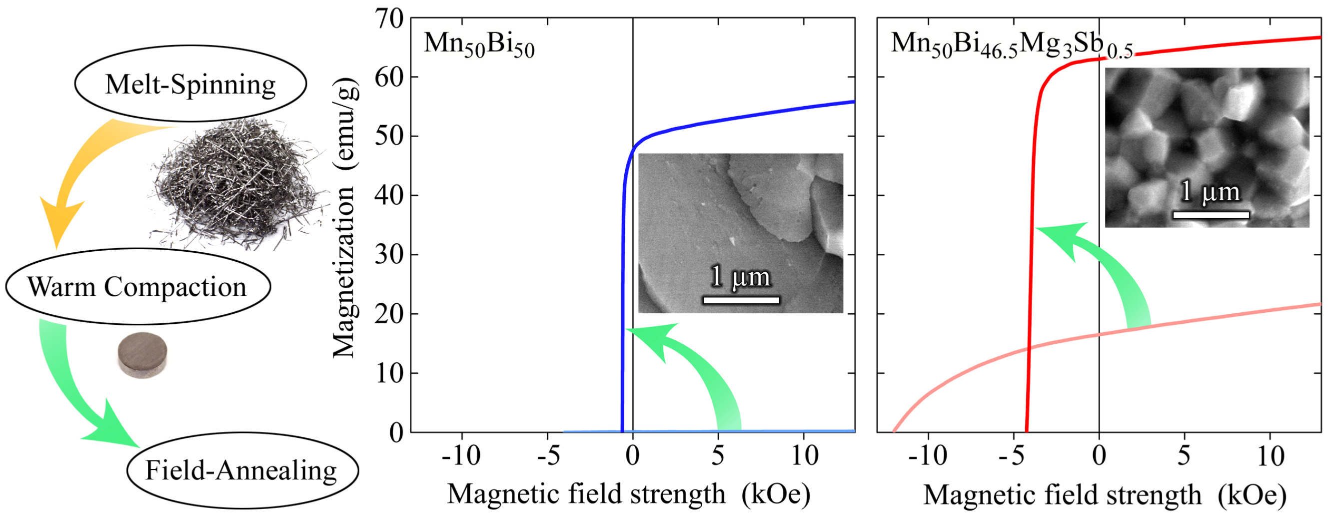
Summary

- MnBi
  - Saturation magnetization of feedstock powder was improved from 65 to 79 emu/g
  - Energy product was improved from 8.5 to 12 MGOe (lab scale)
  - 80 pieces of large bulk magnet with 8.2 MGOe were produced
- 6.5% Si steel
  - Relationship between physical properties and cooling rate was established
  - Flake production method and capacity were established
  - Laminate inner structure was optimized and fabrication method was established
- Motor
  - 10 kW 400 Hz motor was designed.
  - Construction of the 1st prototype was finished in Oct. 2019
  - Testing of the prototype was finished in June 2020

Technical Backup Slides

Next generation MnBi-X magnet

- Extensive composition optimization effort resulted in an improvement in energy product to 12 MGOe
- The addition of 3rd and 4th elements dis-stable the α-MnBi, make it more susceptible for magnetic annealing, thereby achieving optimum magnetization and coercivity.



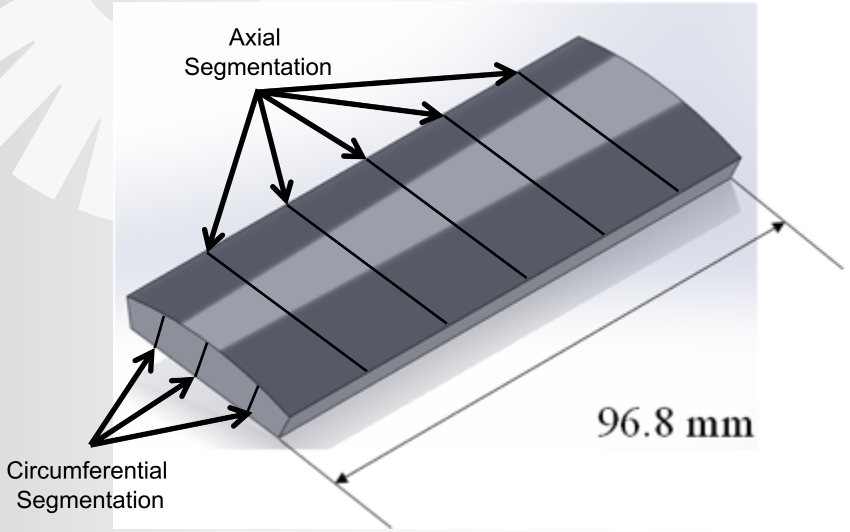
Exploratory work was carried out by the team at Univ. Delaware (Dr. A Gabay and G Hadjipanayis)

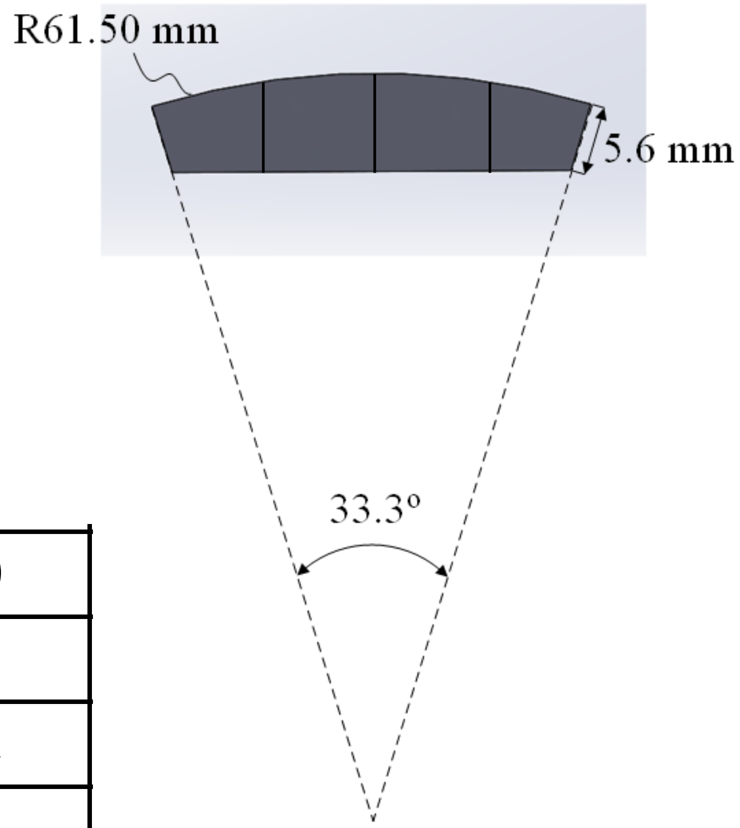
Composition[a]	T_{comp} (°C)	B_r (kG)	H_{ci} (kOe)	$(BH)_{max}$ (MGOe)
$Mn_{50}Bi_{50}$	150	5.4	0.6	2.1
$Mn_{50}Bi_{48.5}In_{1.5}$	150	5.8	1.0	3.8
$Mn_{50}Bi_{47}Sn_3$	150	6.0	0.5	2.2
$Mn_{50}Bi_{48.5}Sb_{1.5}$	150	4.7	7.4	5.1
$Mn_{50}Bi_{47}Mg_3$	150	6.8	3.4	9.8
$Mn_{50}Bi_{46}Mg_3Ca$	150	6.5	1.1	4.8
$Mn_{50}Bi_{46.5}Mg_3Co_{0.5}$	150	6.3	5.2	9.2
$Mn_{50}Bi_{46.5}Mg_3Cu_{0.5}$	150	7.0	1.8	7.8
$Mn_{50}Bi_{46.5}Mg_3Zn_{0.5}$	150	7.6	1.8	6.7
$Mn_{50}Bi_{46.5}Mg_3Ga_{0.5}$	150	6.5	4.8	9.9
$Mn_{50}Bi_{46.5}Mg_3Zr_{0.5}$	150	6.4	3.7	8.6
$Mn_{50}Bi_{46.5}Mg_3Ce_{0.5}$	150	6.2	4.2	7.6
$Mn_{50}Bi_{46.5}Mg_3In_{0.5}$	150	7.1	4.7	11.6
$Mn_{50}Bi_{46}Mg_3In$	150	7.2	4.4	11.4
$Mn_{50}Bi_{46.5}Mg_3Sb_{0.5}$	150	7.0	5.6	11.5
$Mn_{50}Bi_{46.25}Mg_3Sb_{0.75}$	150	6.5	6.4	9.9
$Mn_{50}Bi_{46}Mg_3Sb$	150	6.4	8.2	9.5
$Mn_{50}Bi_{45.5}Mg_3Sb_{1.5}$	150	5.9	9.3	8.1
$Mn_{50}Bi_{46}Mg_3Co_{0.5}Zn_{0.5}$	150	6.3	5.1	9.0
$Mn_{50}Bi_{46}Mg_3Cu_{0.5}Sb_{0.5}$	150	5.7	6.3	7.4
$Mn_{50}Bi_{46}Mg_3Ga_{0.5}Sb_{0.5}$	150	6.5	5.0	9.9
$Mn_{50}Bi_{46}Mg_3In_{0.5}Sb_{0.5}$	80	7.1	7.1	12.0
$Mn_{50}Bi_{45}Mg_3In_{0.5}Sb_{1.5}$	150	6.7	9.4	10.6

Magnets used in this project

	Axial	Circumferential
Number of segments	4	5-10

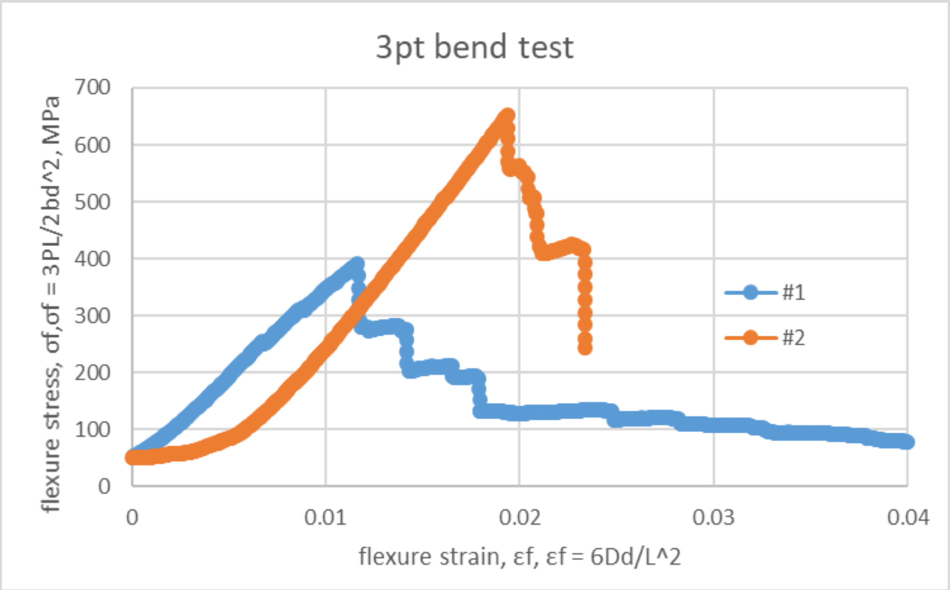
Mn-Bi magnet geometry



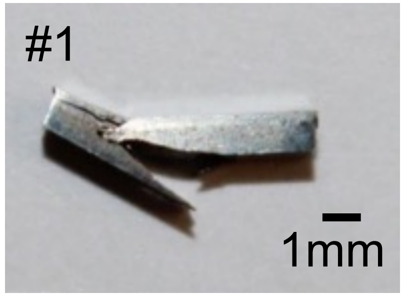


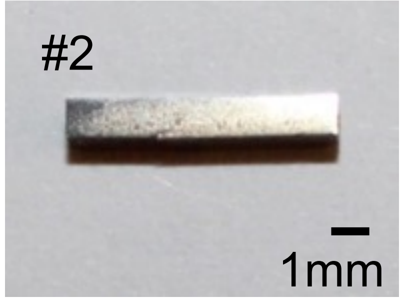
Br [kG]	6.0
Hc [kOe]	5.1
Hci [kOe]	6.2
Bhmax [MGOe]	8.4

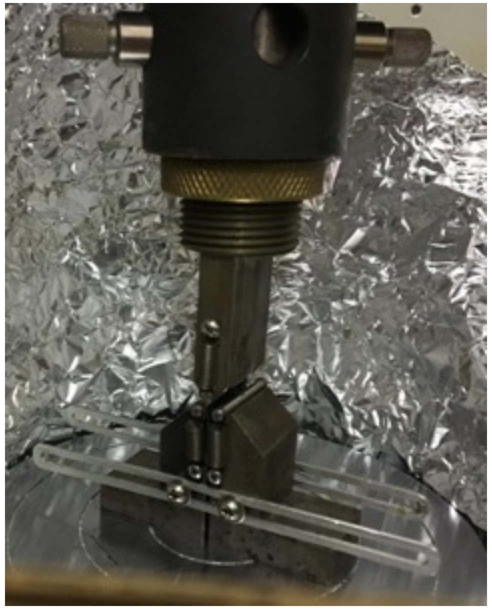
Mechanical Properties



3pt bending test of flake-consolidated FeSi sample







Sample #1 has pre-existing crack

The mechanical properties of the CaF_2 coated is remarkable

- High bending strength (650MPa)
- CaF_2 interlayer bonding prevented the sample from catastrophic failure on breakage.